Longitudinal Effects in the Fermilab Booster

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Collaborators

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- Bill Pellico

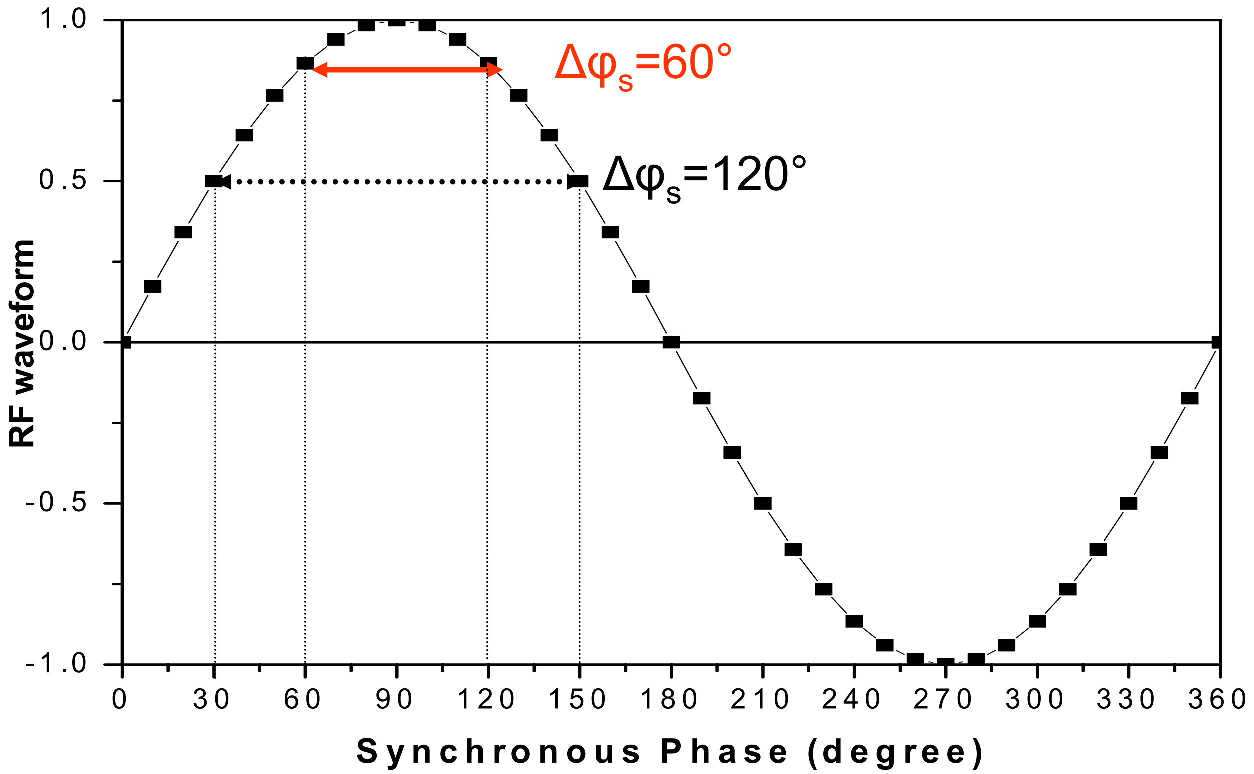
Questions
-- we try to answer

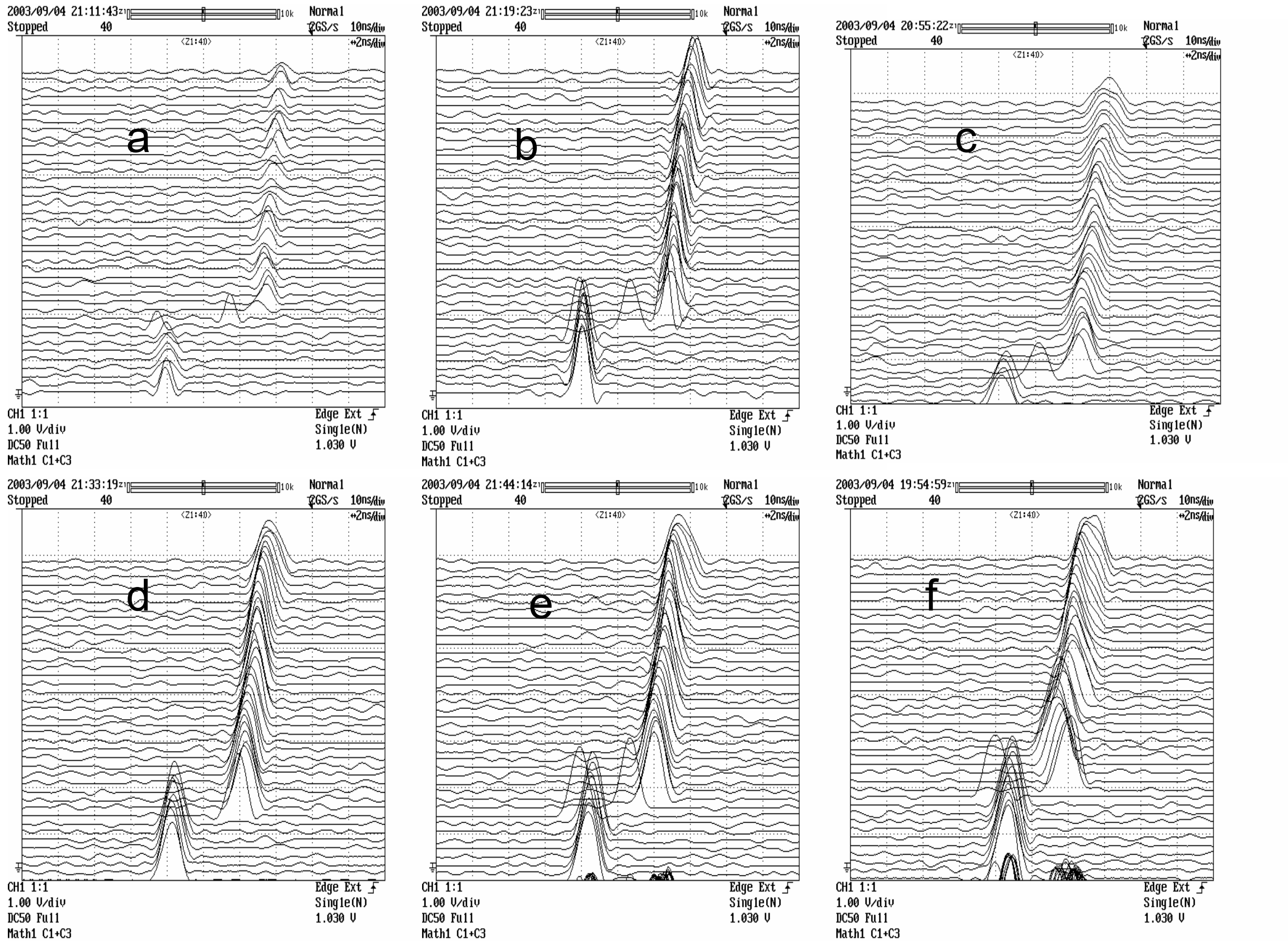
- Do we have enough RF power as the intensity increases? If so, would it help the problem by adding 30 Hz harmonic to slow the accelerating ramp?
- Do we need to use γ_t system to provide a faster transition crossing?

Outline

1. Measuring the phase jump at the transition crossing to estimate whether or not running out of RF power.
2. Developing diagnostic tool to measure the particle distribution in the longitudinal phase space.
3. Experimentally investigating the relationship between the beam energy loss and the beam intensity in both the *6-GeV* slow acceleration and the *8-GeV* normal acceleration.
4. Developing experimental procedures for solving the γ_t quad-steering problem, which is essential for the commission of the γ_t system.

1.Phase jump at the transition cross as indicator of whether or not run out of RF power?



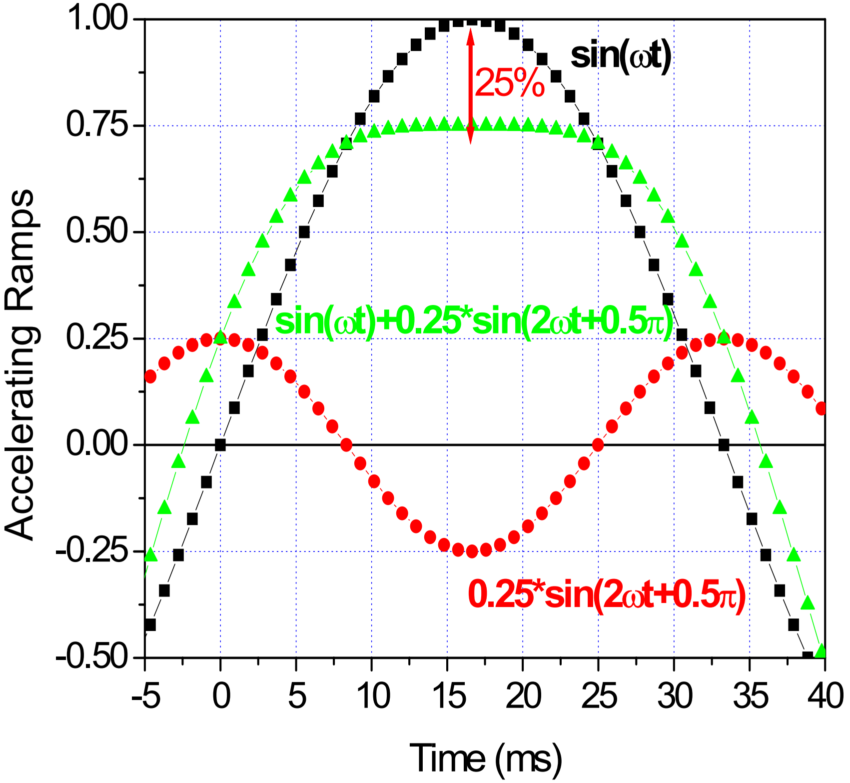


the same Booster bunch was plotted at one trace per 8 Booster turns. The same time scale (2 ns/div). 1(a) the beam intensity is 0.4×10^{12}. 1(b) the beam intensity is 1.2×10^{12}. 1(c) the beam intensity is 1.9×10^{12}. 1(d) the beam intensity is 2.63×10^{12}. 1(e) the beam intensity is 3.5×10^{12}. 1(f) the beam intensity is 5.2×10^{12}.

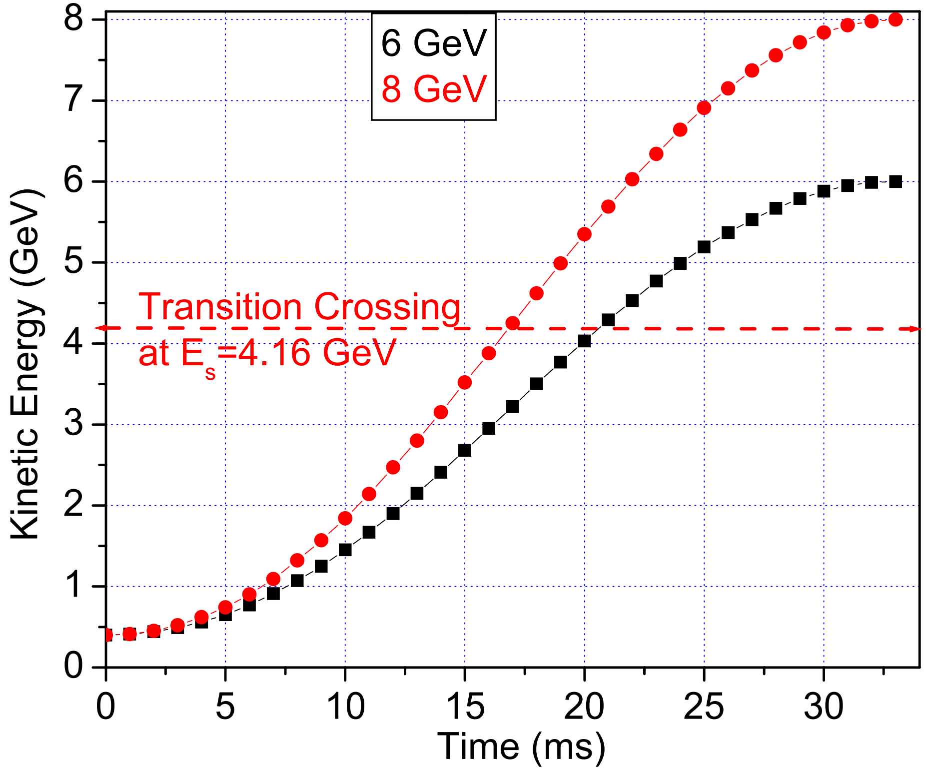
Why 6-GeV study?

- The purpose of the *6-GeV* slow acceleration study is to experimentally investigate the potential benefits by adding 25% 2nd harmonic (30-Hz) to the fundamental (15-Hz) Booster magnetic ramp.

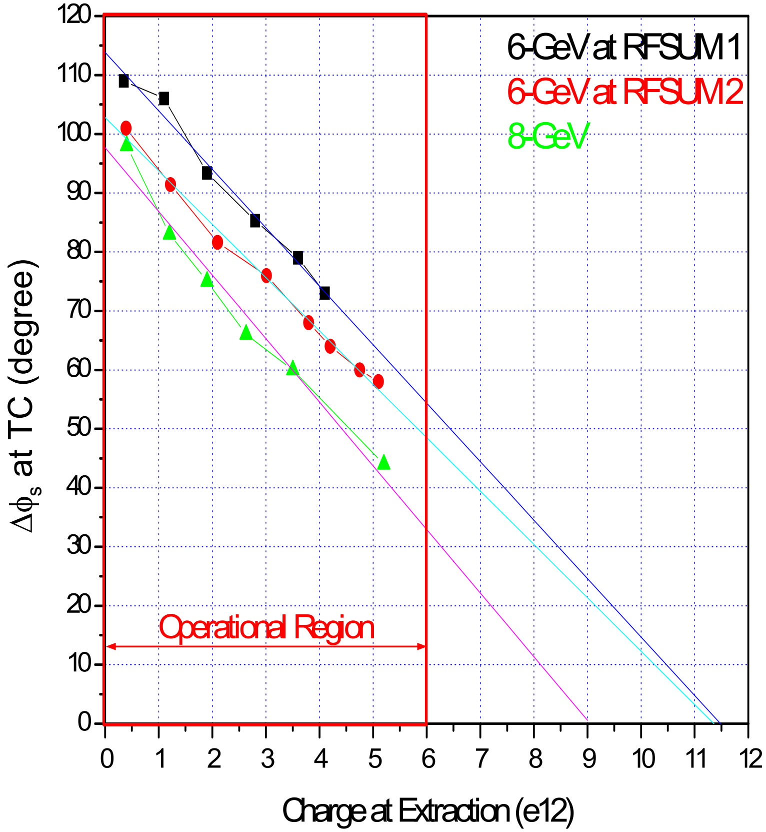
The only thing we can do now is to rescale the 8 GeV ramp to 6 GeV ramp.



6 GeV Acceleration and 8 GeV Acceleration



The phase jump decreases with the increase of the beam intensity



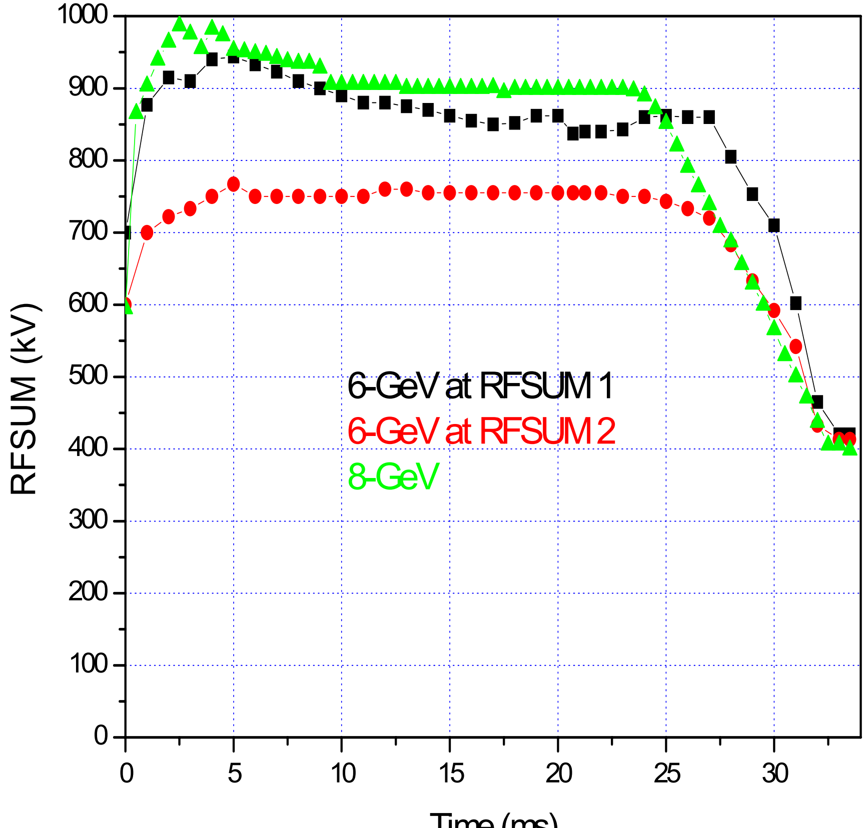
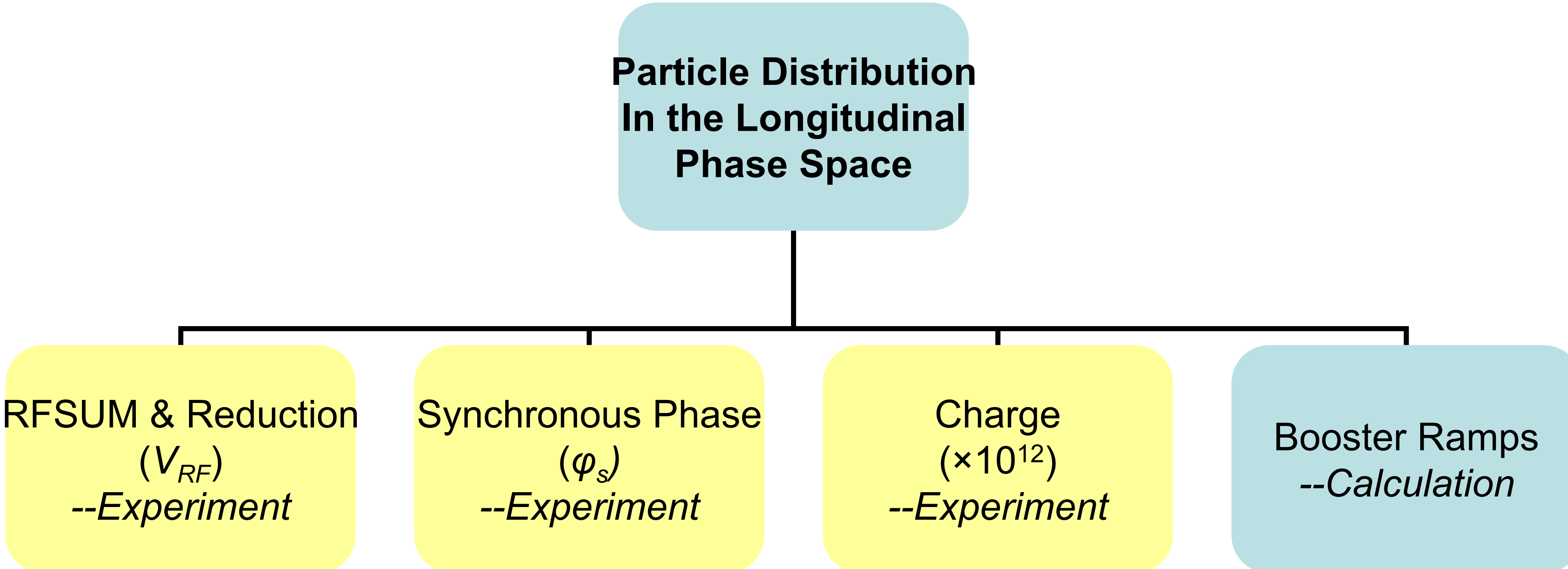


Fig. 1(a)

2. Diagnostic tool to determine

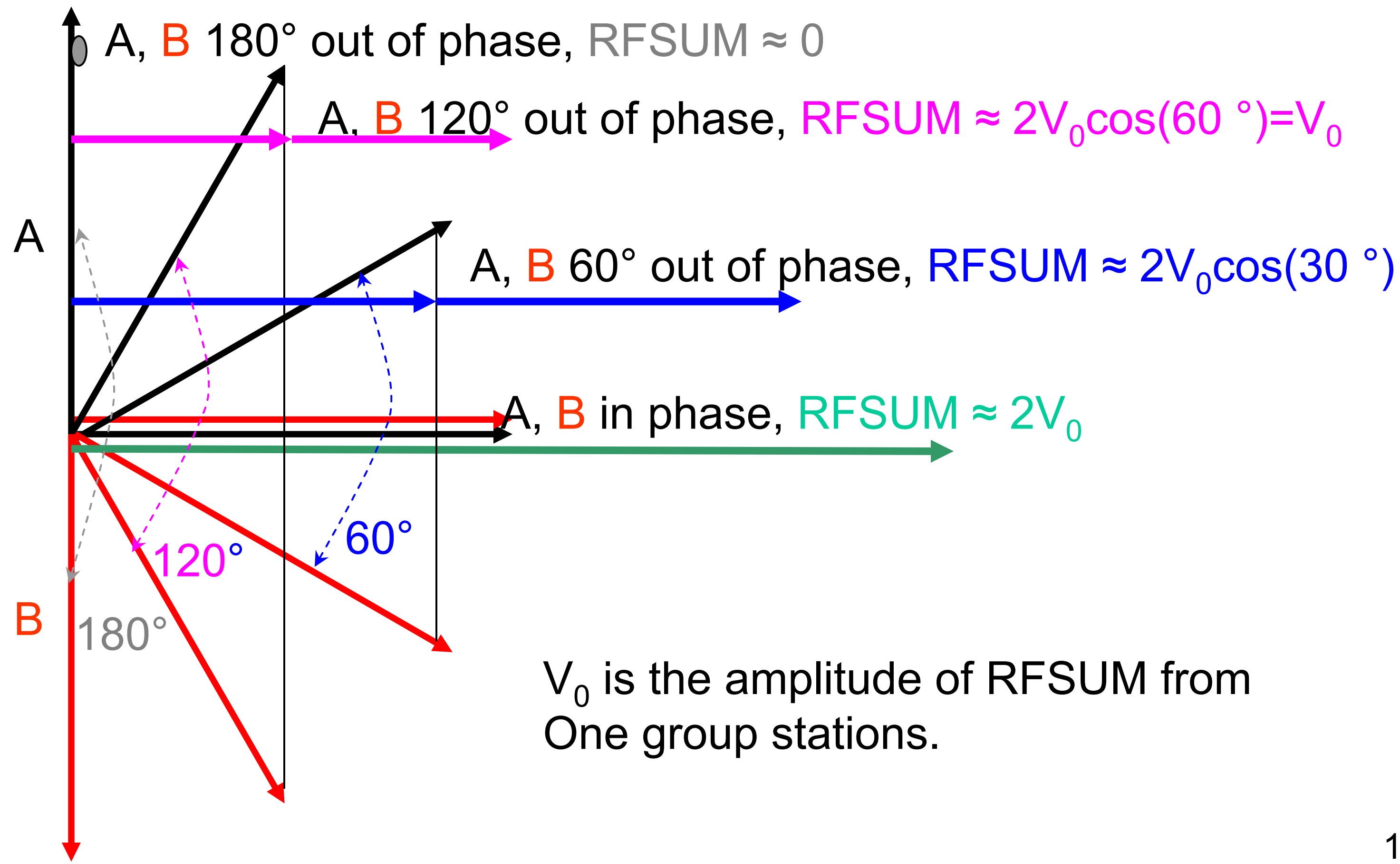


Bucket Area A (eV · s)

$$A = \frac{16 \cdot \beta}{2 \cdot \pi \cdot f_{rf}} \cdot \sqrt{\frac{e \cdot V_{RF} \cdot E_s}{2 \cdot \pi \cdot h \cdot |\eta|}} \cdot \alpha(\varphi_s).$$

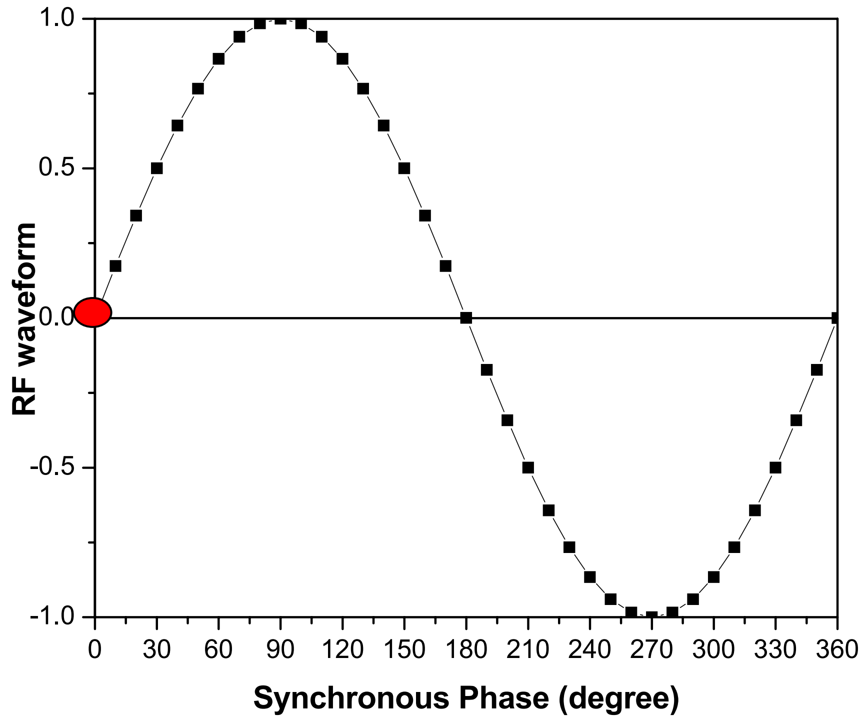
RFSUM Reduction *via* the Phase Rotation between Group-A Stations and Group-B Stations

In general, it is true that RFSUM of group-A stations is equal to RFSUM of group-B stations. The phase rotation is controlled by the paraphase module.

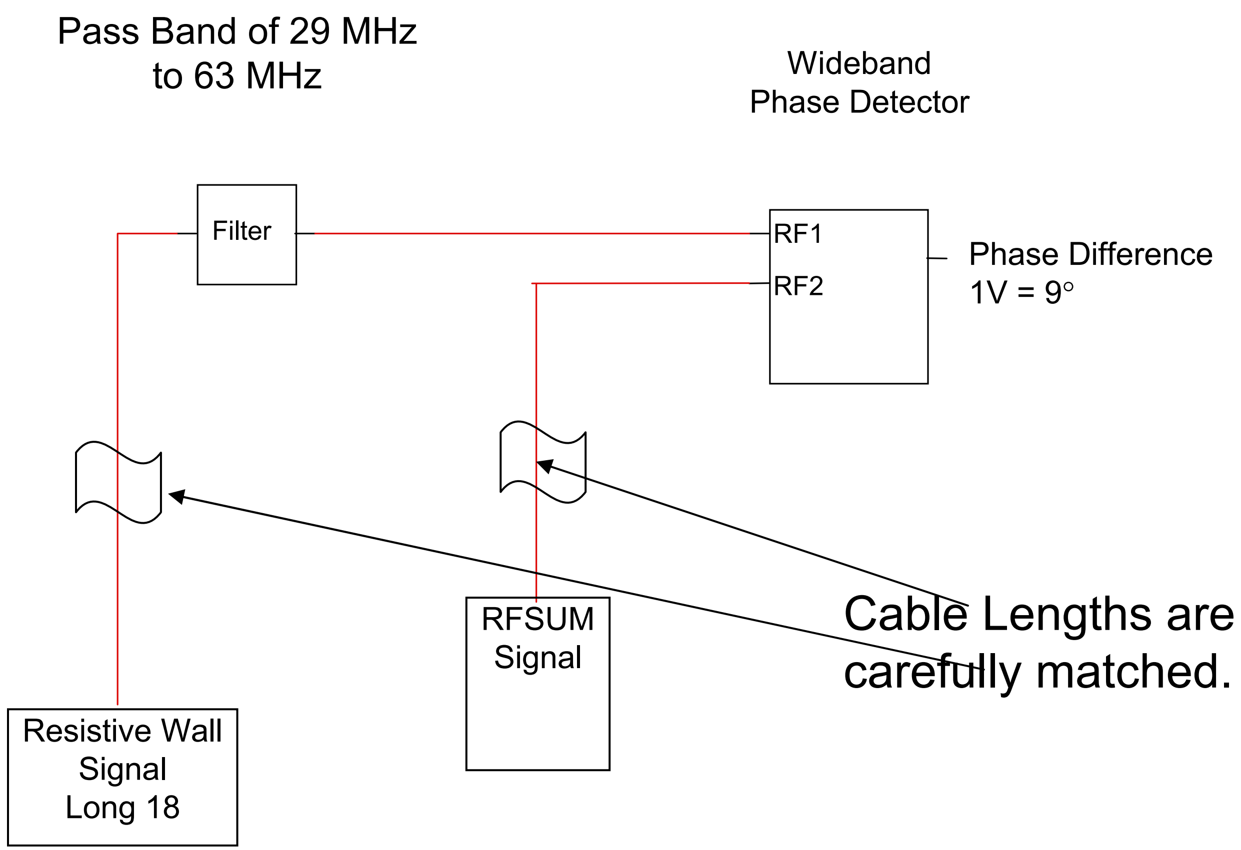


V_0 is the amplitude of RFSUM from One group stations.

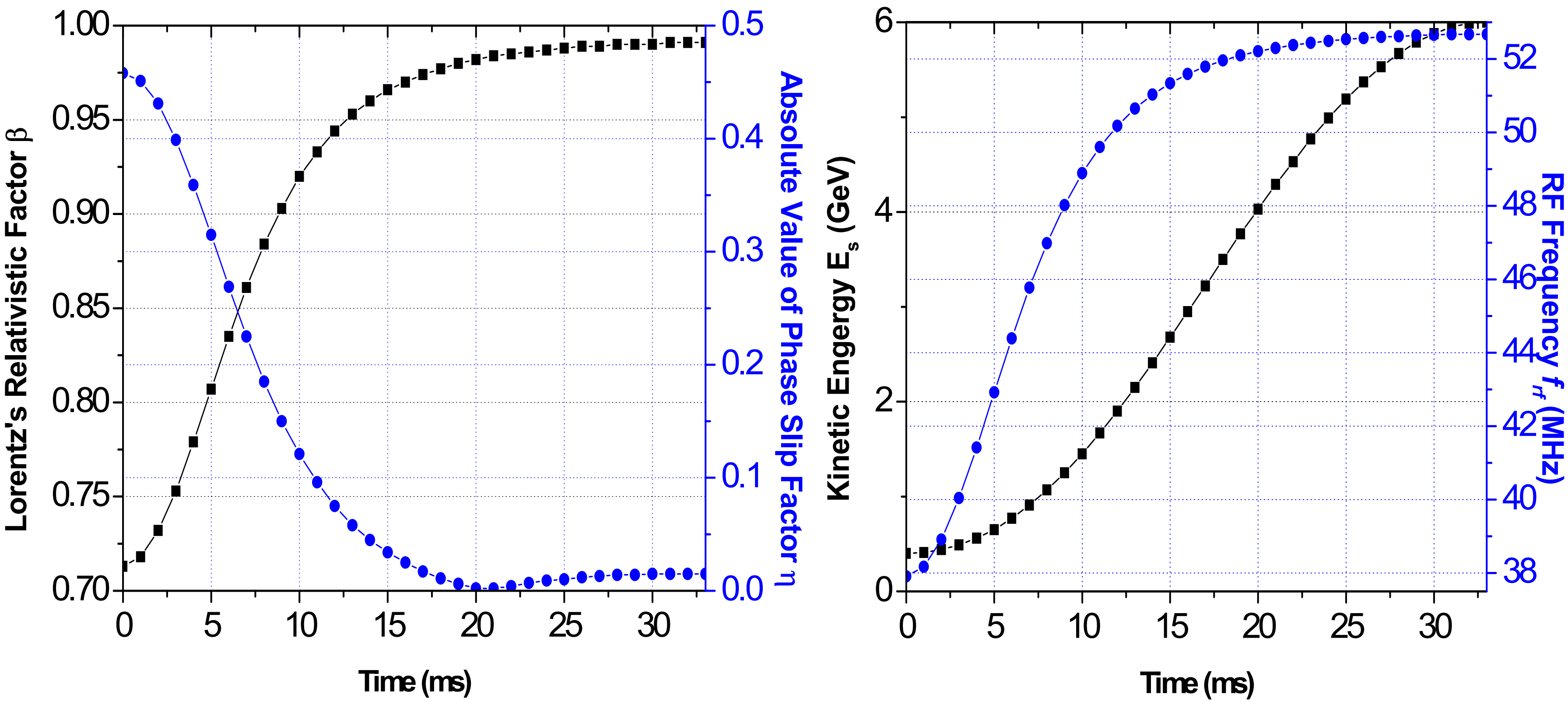
Synchronous Phase is the phase of the ideal particle relative to the RF waveform



Schematic of the Synchronous Phase Detector (SPD)



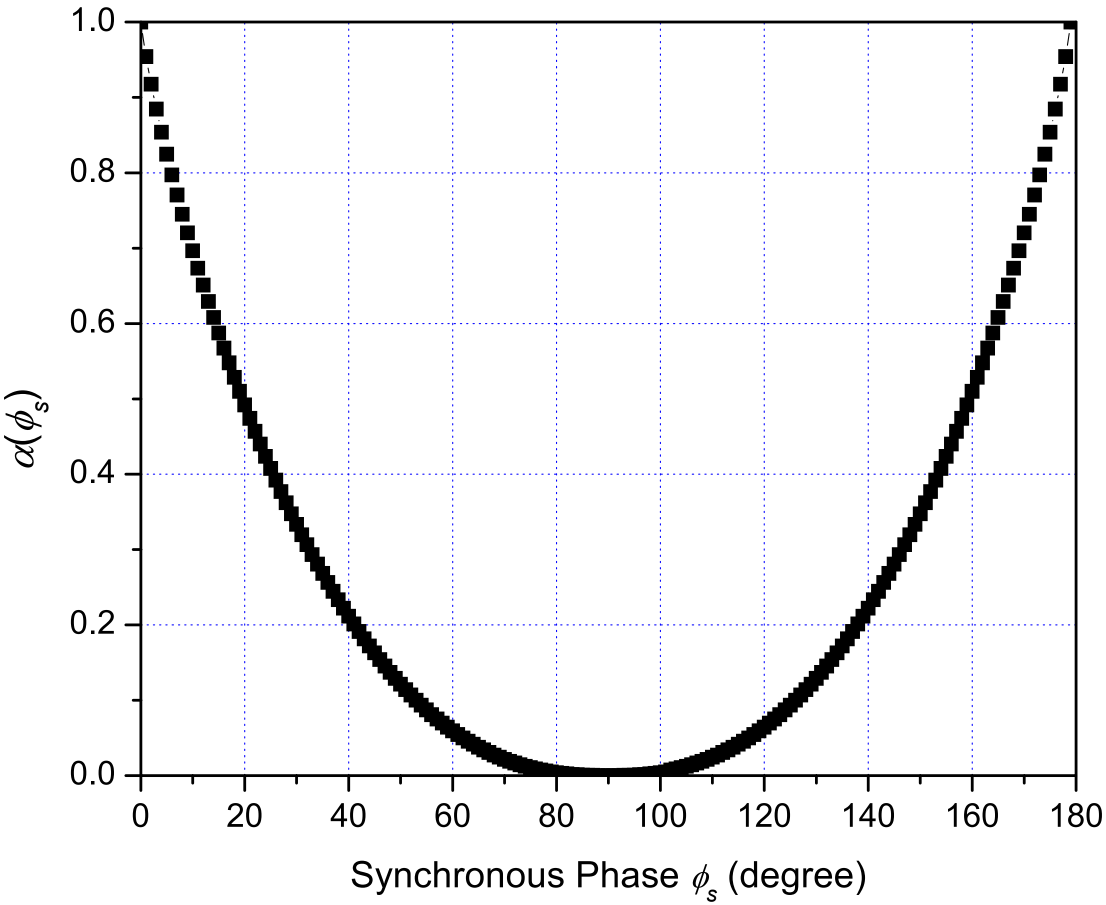
Booster 6-GeV Ramps



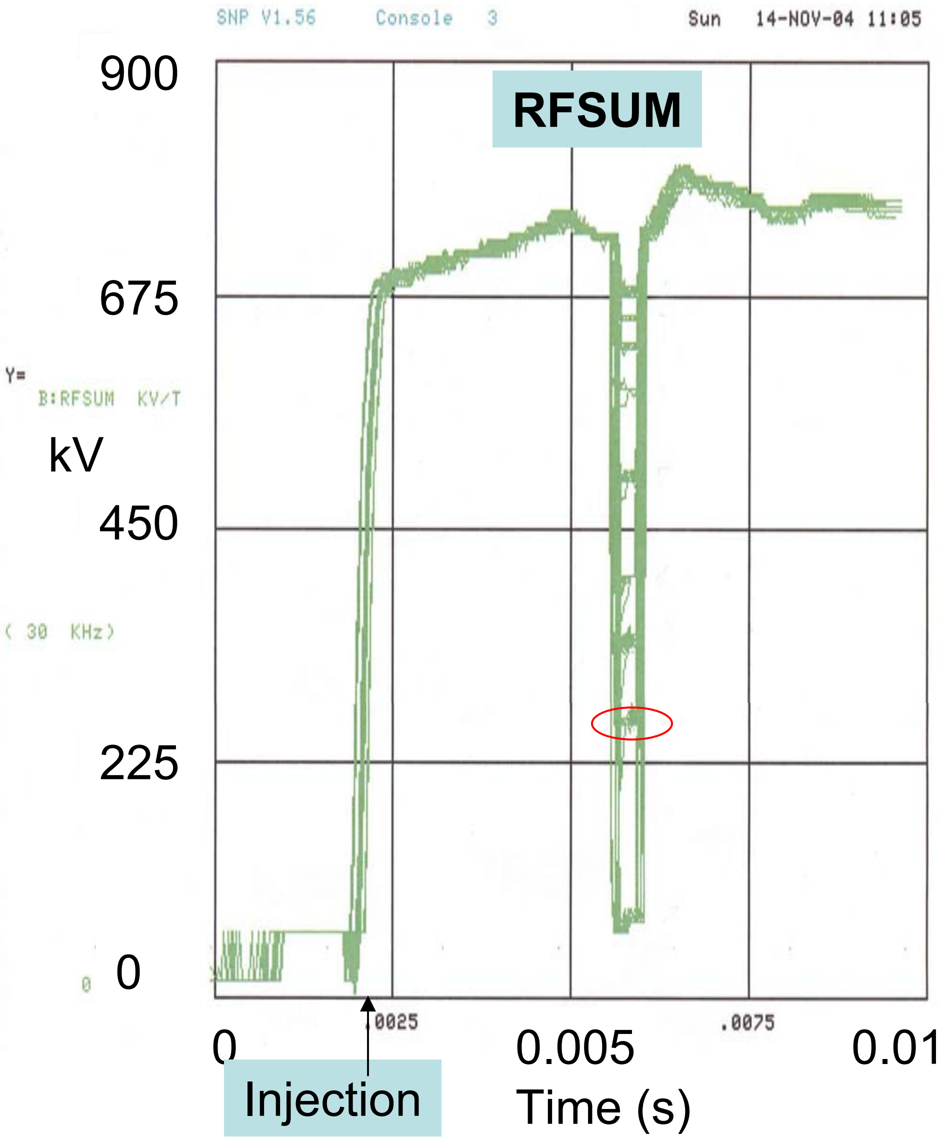
Moving bucket factor $\alpha(\varphi_s)$:

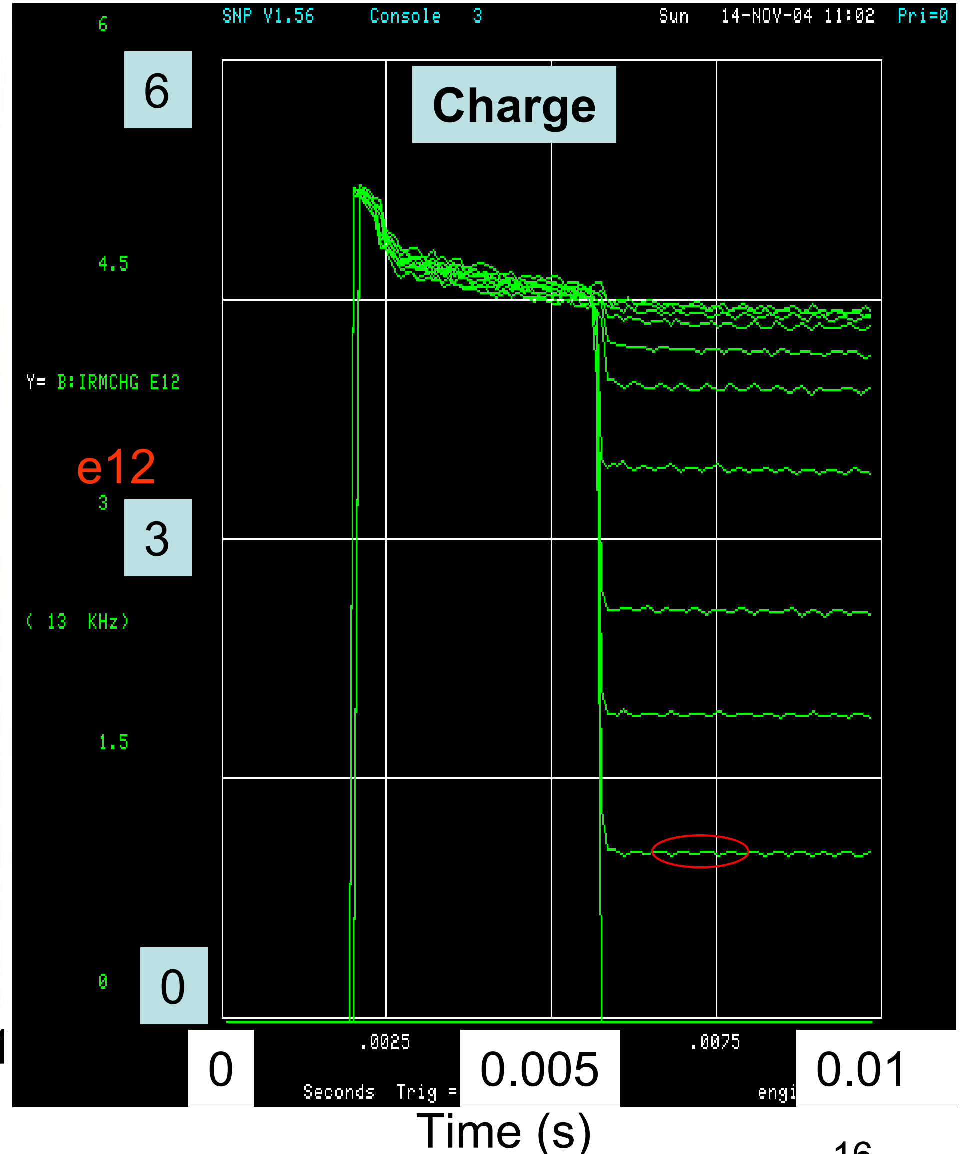
the ratio of the bucket area with φ_s relative to the stationary bucket area (either φ_s=0°, or φ_s=180°)

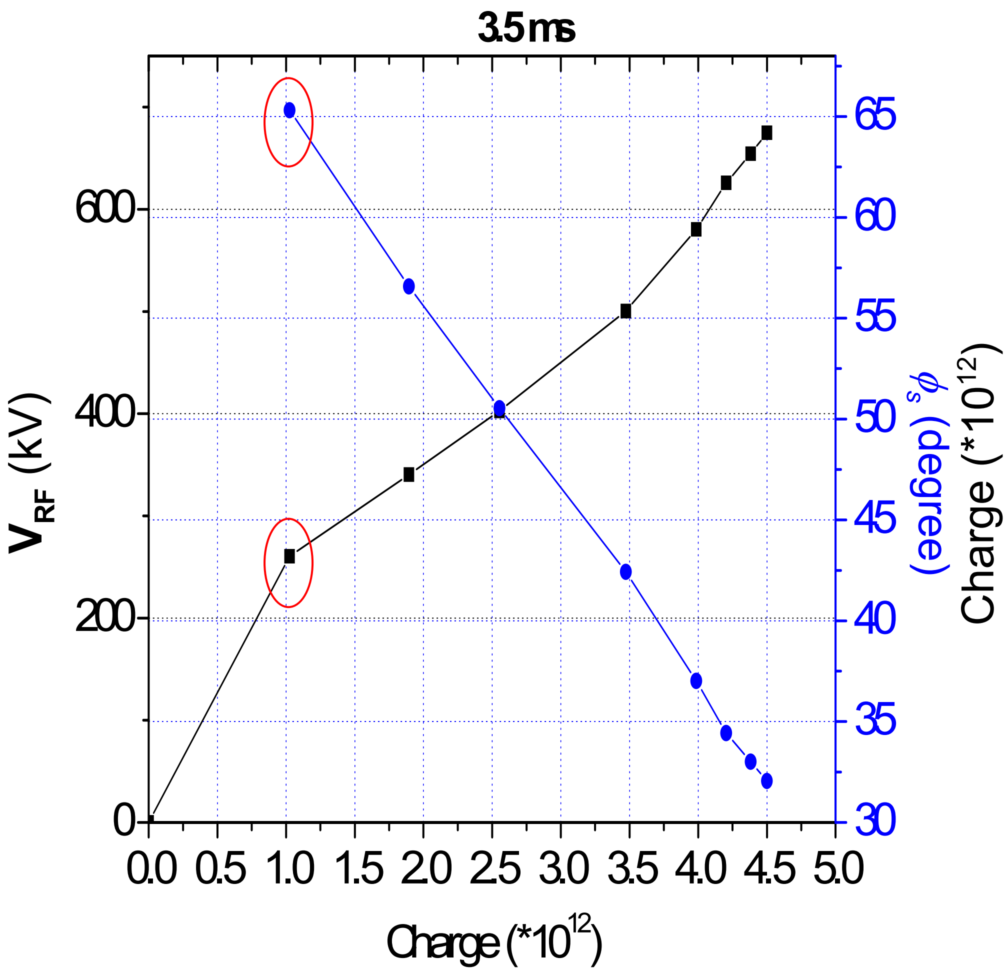
h=84 is the harmonic number

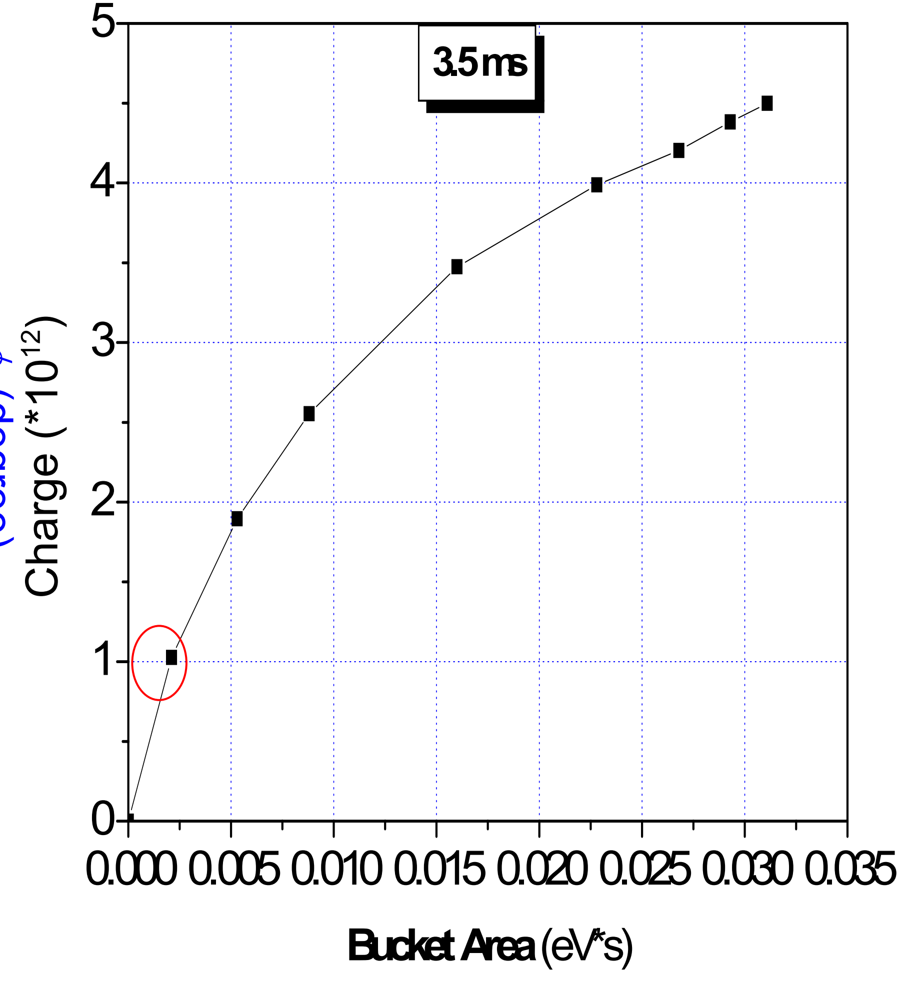


Example: Signals at 3.5 ms after Injection

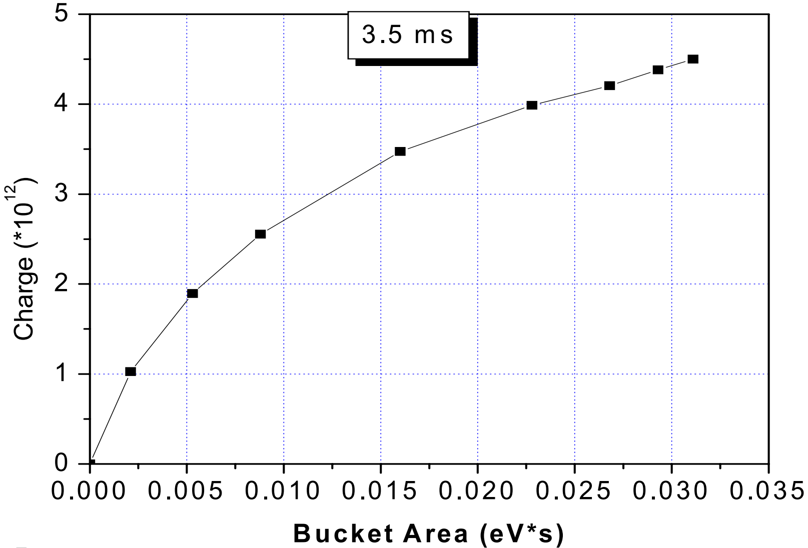


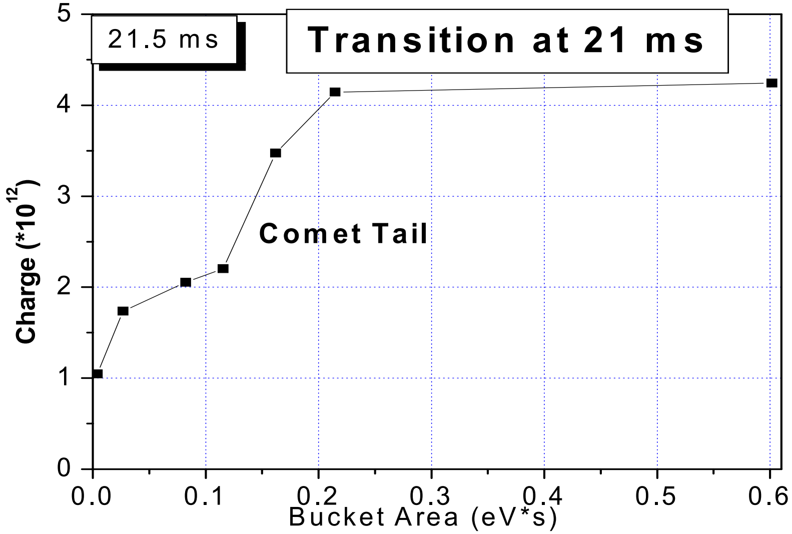


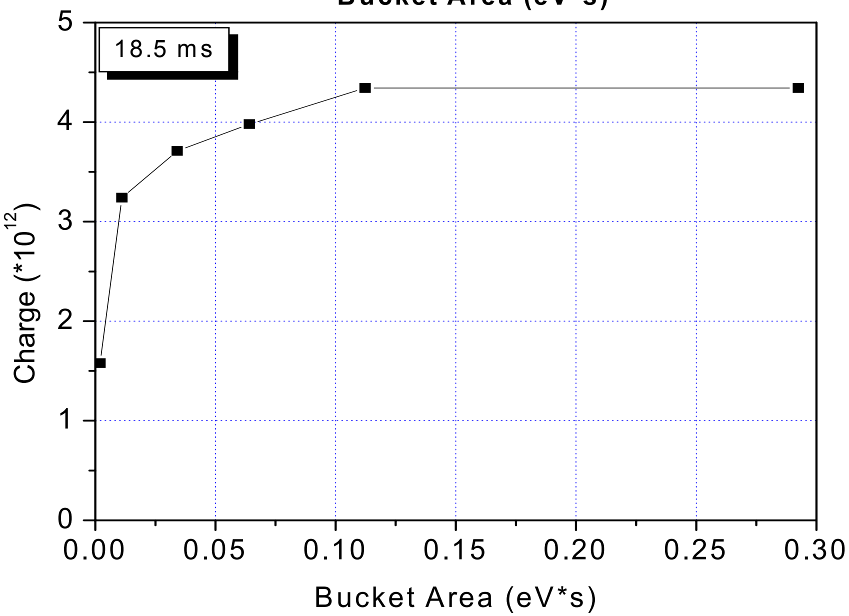

3.5ms
V_{RF} (kV)
ϕ_s (degree)
Charge (*10[12])

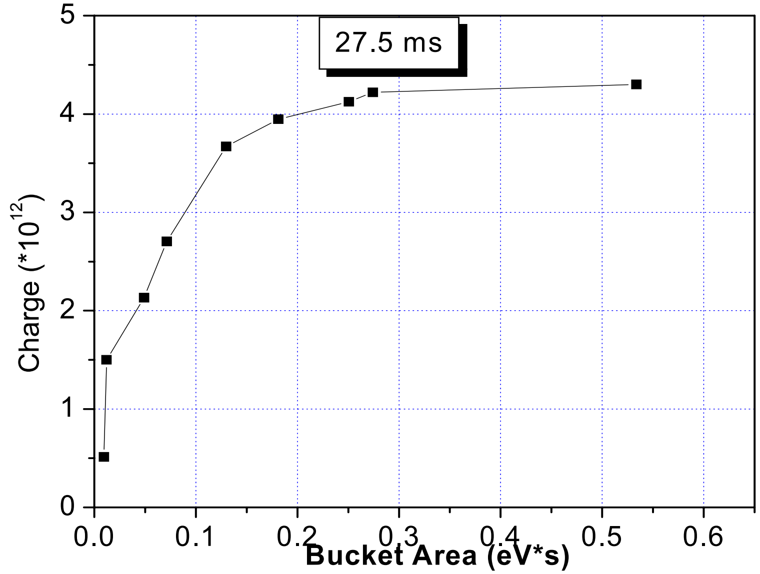

3.5ms
Charge (*10[12])
Bucket Area (eV*s)

Charge vs. Bucket Area at 3.5 ms, 18.5 ms, 21.5 ms, and 27.5 ms

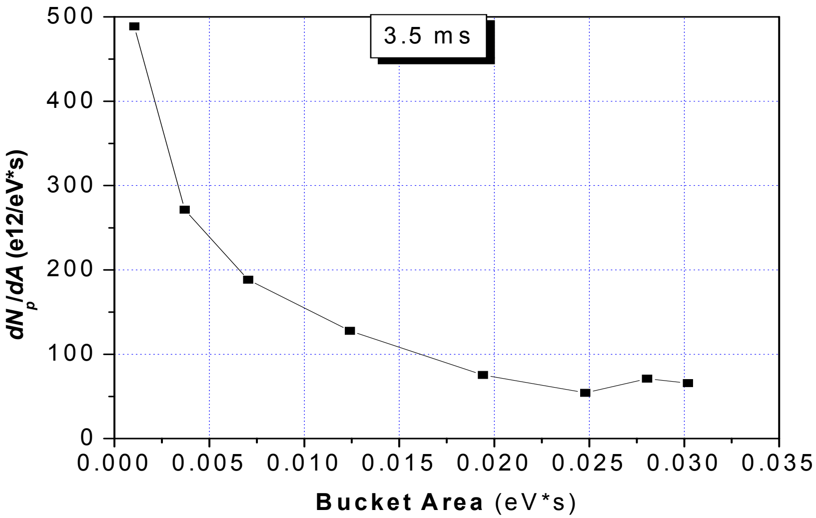


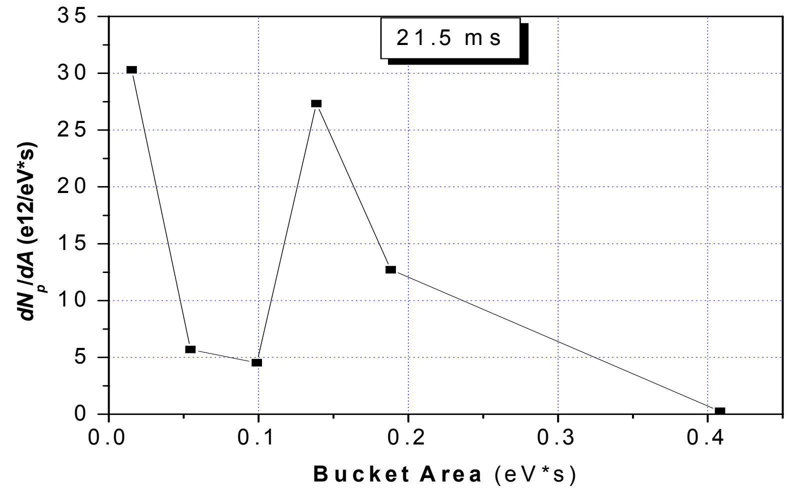


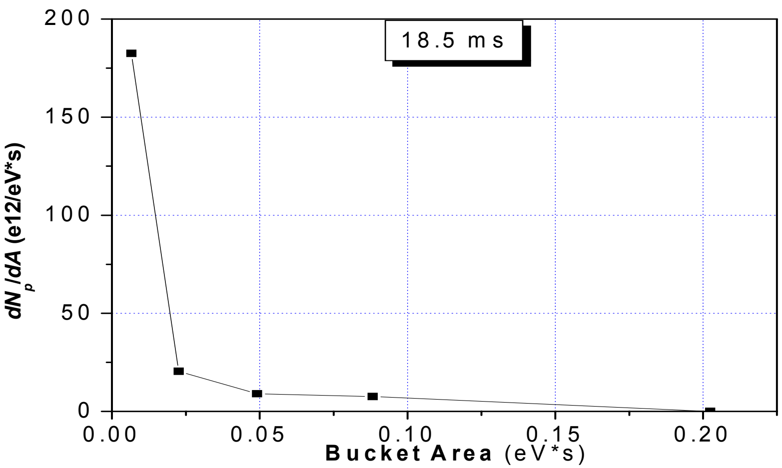


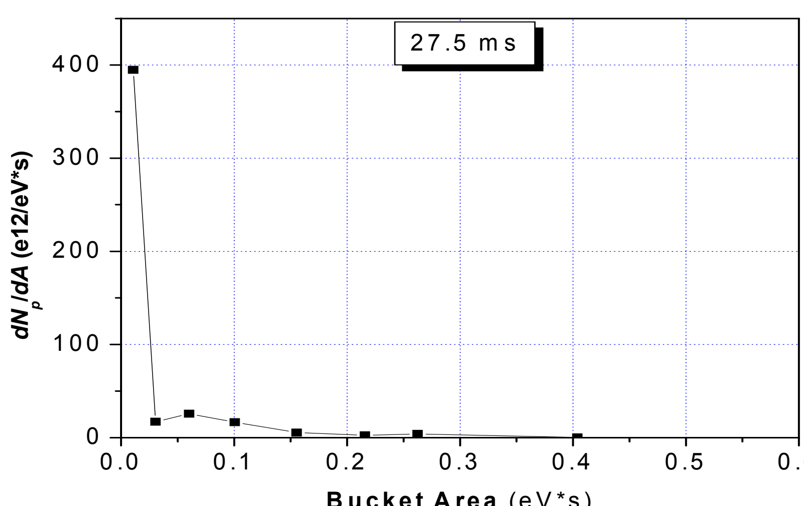


Charge Density vs. Bucket Area at 3.5 ms, 18.5 ms, 21.5 ms, and 27.5 ms

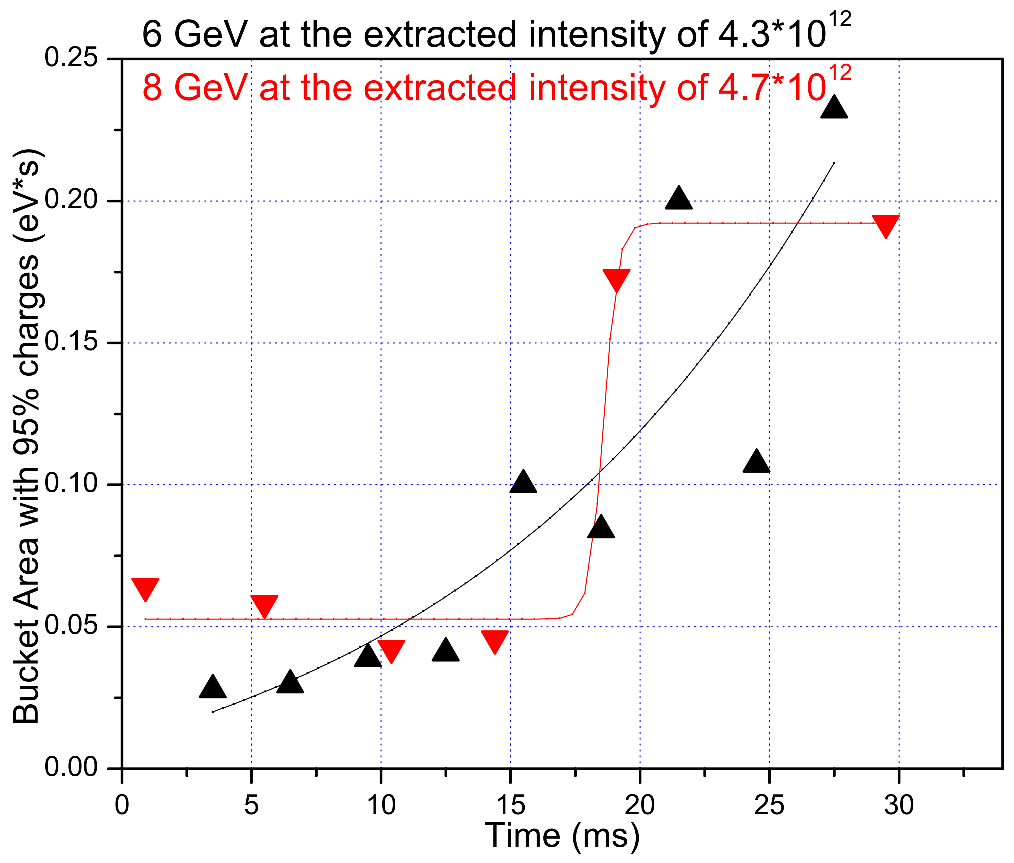








Comparison of the Bucket-Area Measurement at 6GeV and 8GeV



3.Analyzing the dependence of the beam energy loss (V_L) on the beam intensity

$$V_{eff} = V_a + V_L = V_{RF} \times \sin(\varphi_s).$$

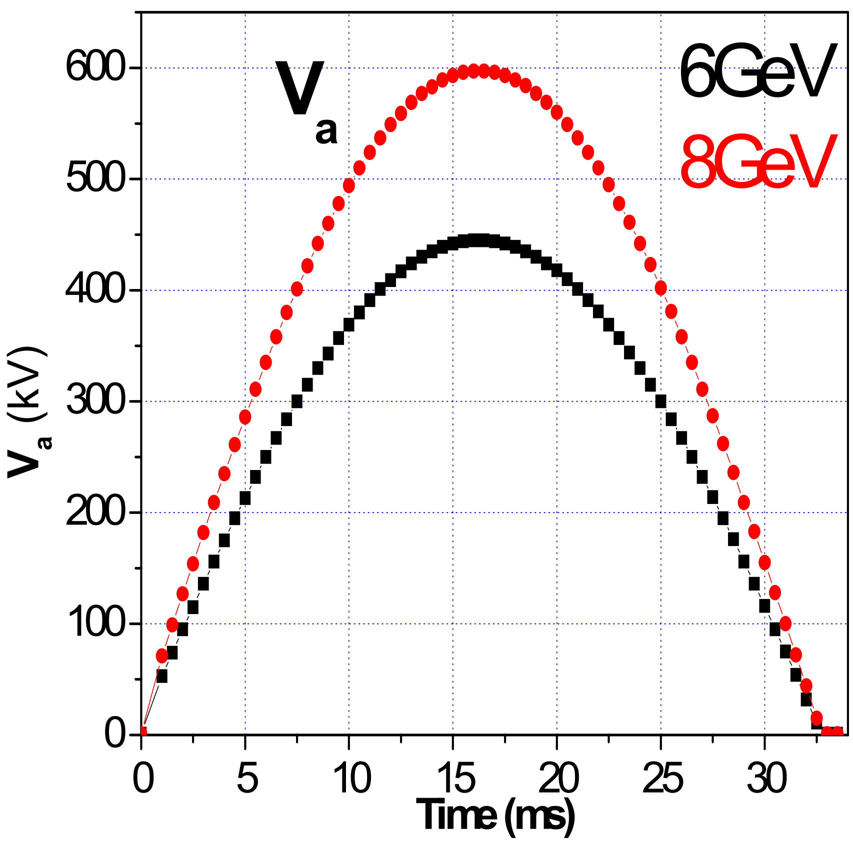
V_{eff}: the effective accelerating voltage seen by the beam per Booster turn.

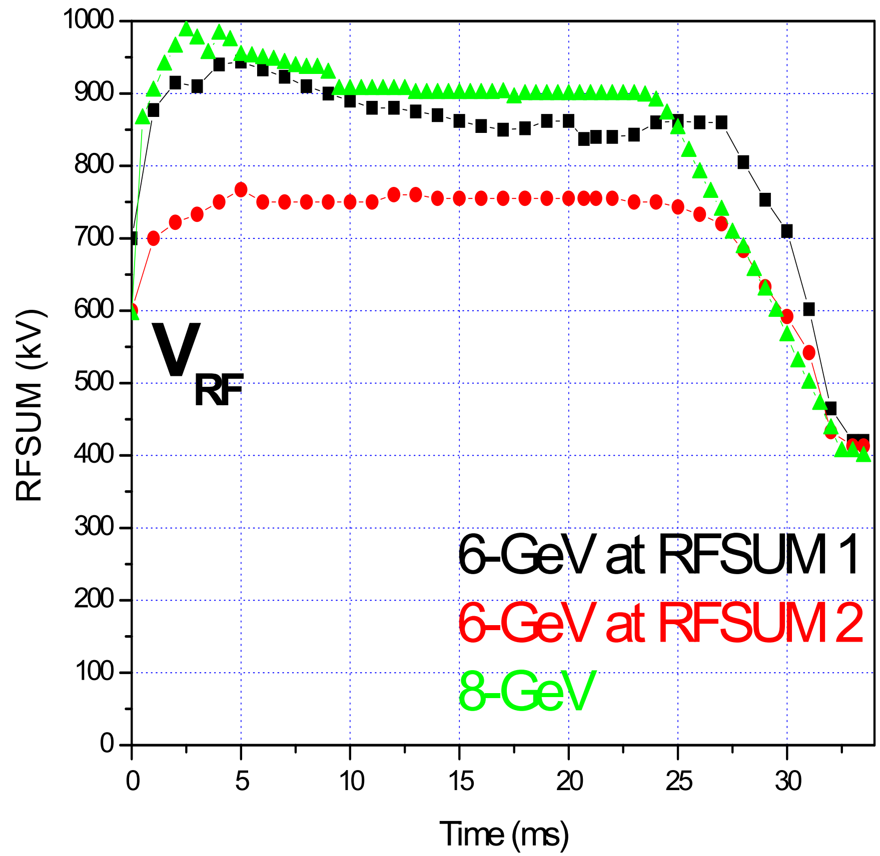
V_a: the accelerating voltage required by the rate of change of the Booster magnetic field (dB/dt) in a cycle, and is independent of the beam intensity.

V_L: the beam energy loss, which is caused by the real impedance of the ring, and is dependent upon the beam intensity with a relation of

$$V_L = a \times N + b.$$

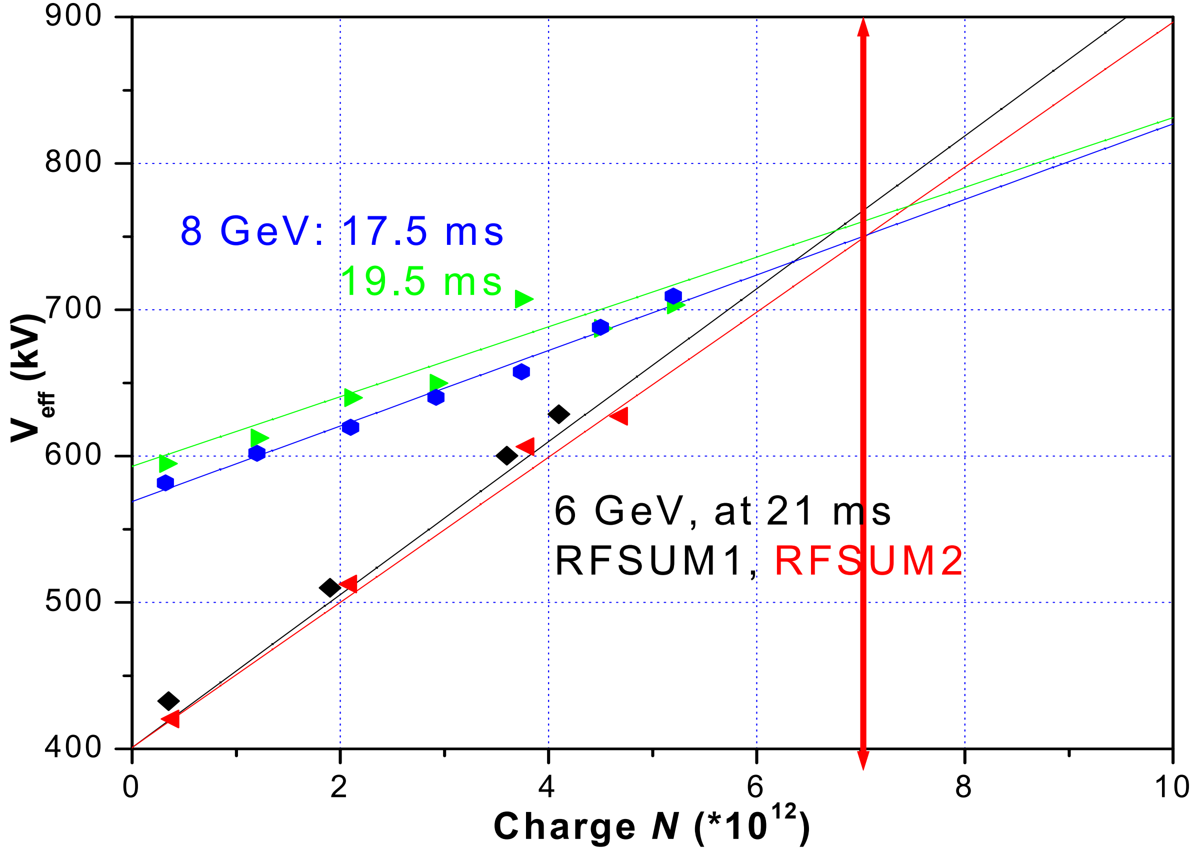
Here, N is the beam intensity (charge); b is DC component of V_L; a is the linear dependence Of V_L to N.





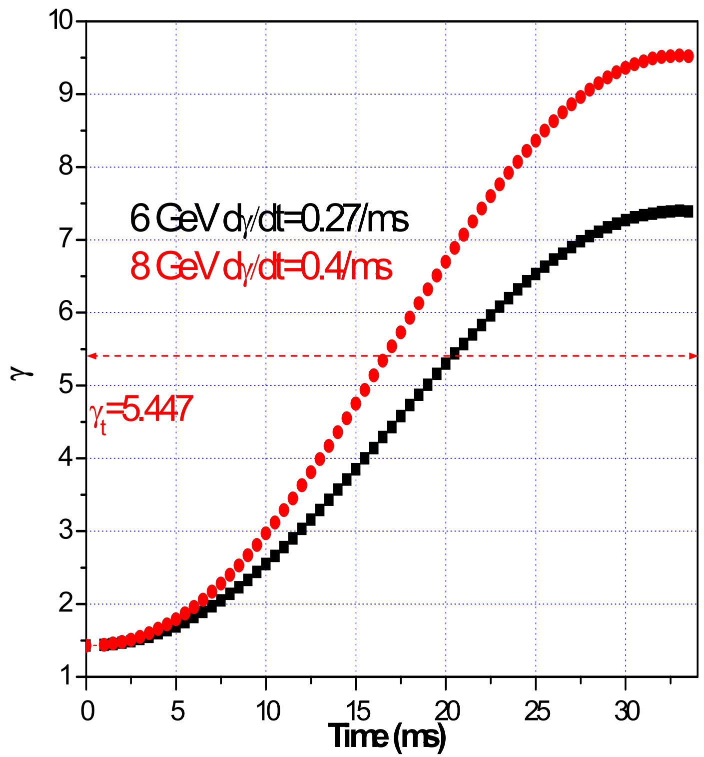
$$V_{eff} = V_a + V_L = V_{RF} \times \sin(\varphi_s).$$

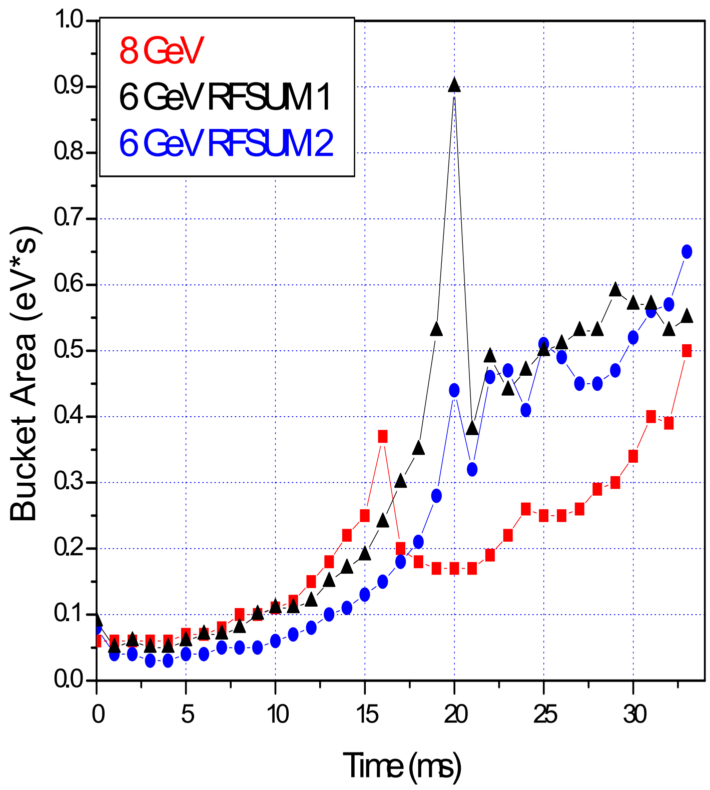
$$V_L = a \times N + b$$



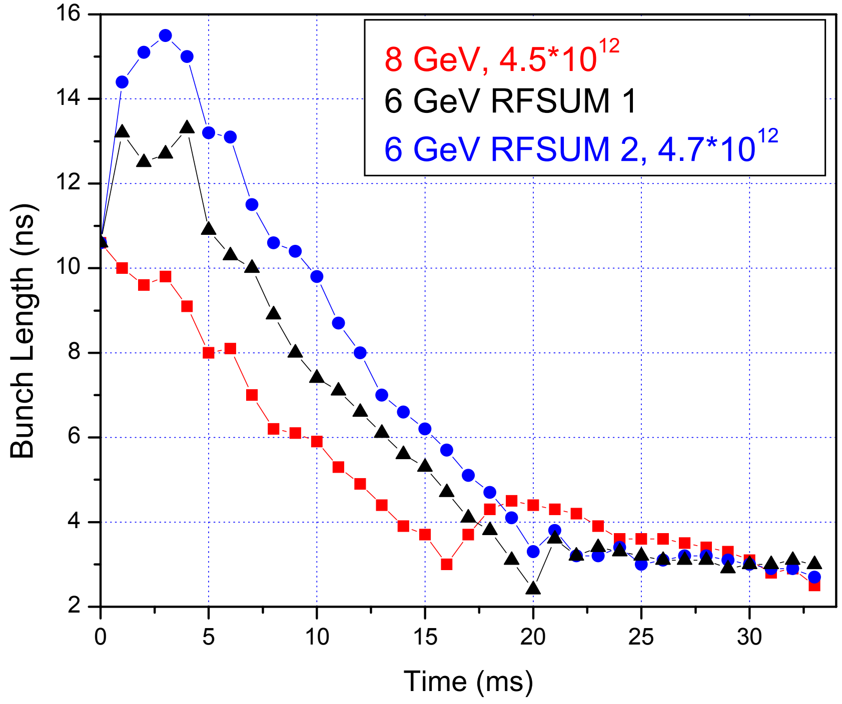
$$a_{8GeV} / a_{6GeV} \approx 23.8 / 49.6 \approx 0.5$$

Possible explanation for the differences in the slope of V_L vs. N





Experimental inputs:RFSUM and synchronous Phase



Slower the transition crossing
↓
Shorter the bunch length
↓
Higher the peak current
↓
Higher the beam energy loss

- 8 GeV at 17.5 ms, BL 4.3 ns,
- 6 GeV at 21 ms, BL 3.2 ns,
- Peak current I_P: $N \cdot e \big/ \sqrt{2\pi}\,\sigma_t$

$$\left(I_{p,8GeV}\right) \big/ \left(I_{p,6GeV}\right) = \left(N_{8GeV} \cdot \sigma_{t,6GeV}\right) \big/ \left(N_{6GeV} \cdot \sigma_{t,8GeV}\right)$$

$$\approx \left(4.5 \big/ 4.7\right) \cdot \left(3.2/4.3\right) \approx 0.71$$

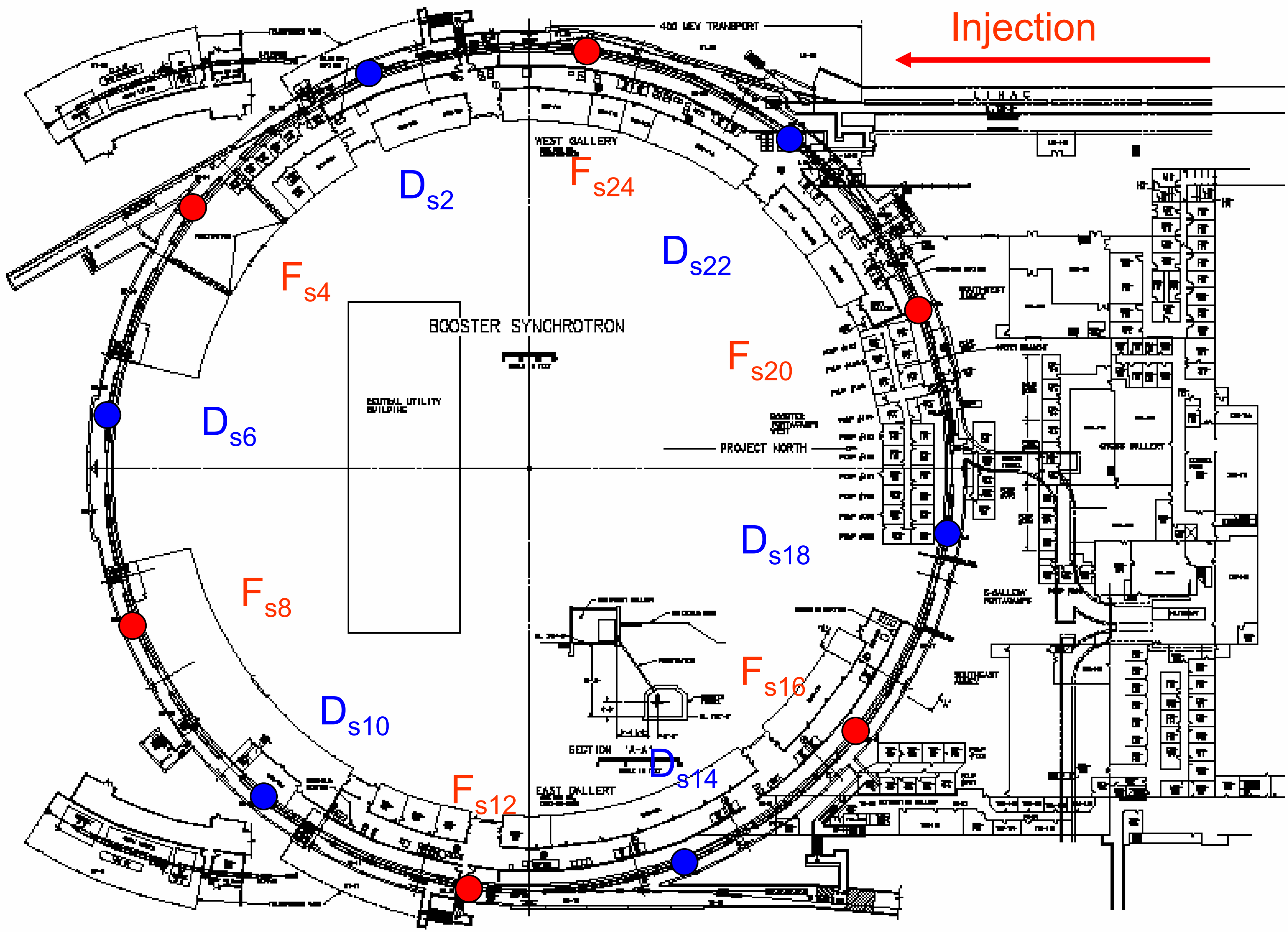
4. Design Goals of the Transition Jump System (γ_t System)

- Change γ_t one unit in 0.1 ms (10 unit/ms) to make the TC 25 times faster than the normal operation (0.4 unit/ms).

--- reducing the deleterious effects of passing through transition at high intensity by reducing the time that the beam spends near the transition energy.

Why the TJS has never been used in the operation?

12 γ_t quads, 6 focusing quads, 6 defocusing quads with 6-fold symmetry arrangement



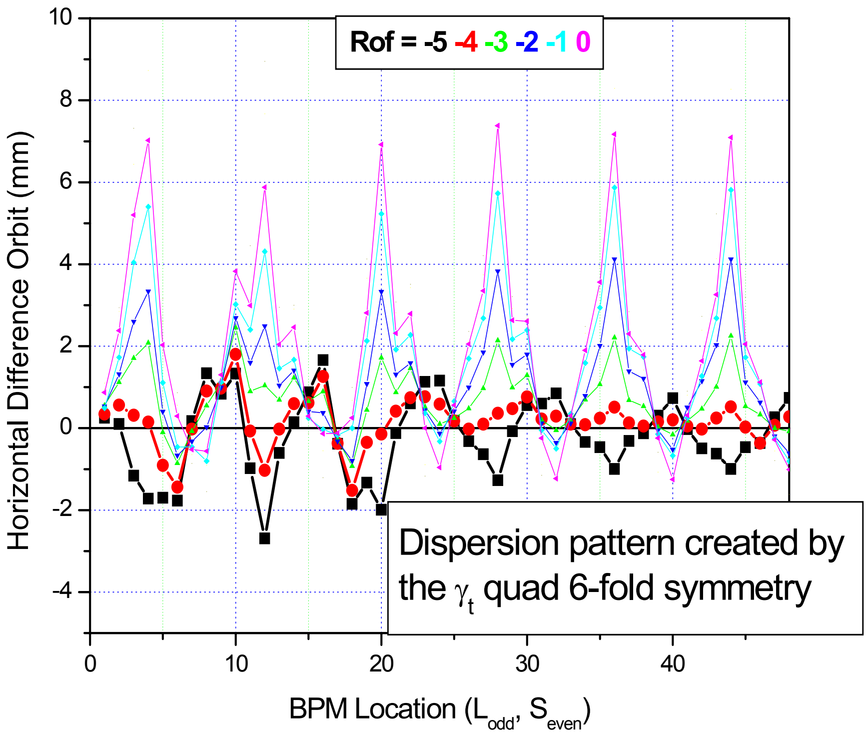
Problem

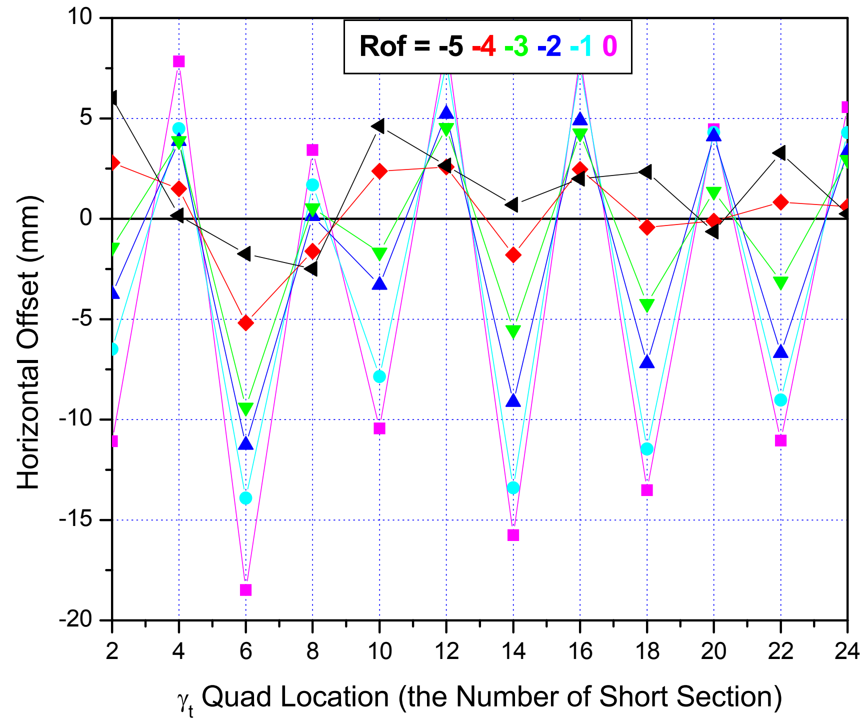
- Quad Steering -- since several γ_t quads are not well aligned relative to the usual closed orbit, quad steering causes beam loss, especially for high intensity beams.

Solution

- Finding Offsets -- a program has been developed for calculating offsets of the beam relative to γ_t quads using the difference orbit when γ_t quads are on and off.
- Horizontal -- A radial orbit offset (ROF) has been experimentally applied in finding the optimal radial position for centering the beam through all the γ_t quads.
- Vertical -- the reposition of the beam to the γ_t quad by applying a local three-bump to the beam or by moving the γ_t quad.

ROF ≈ -4.5 is the optimal radial position for centering the beam through all the γ_t quads





$$\Delta x(s_i) = \sum_{j=1}^{n} \left(\sqrt{\beta(s_j)\times\beta(s_i)} \times \theta(s_j) \times \cos\left(\pi\nu_x - \left|\mu(s_i)-\mu(s_j)\right|\right) \Big/ \left(2\times\sin\left(\pi\times\nu_x\right)\right) \right) = A_{ij}\times\theta(s_j)$$

$$x_j = \theta_j \Big/ (k_j \times l_j), \quad k_j = 0.1128 \text{ at 2000 A short } 4, 8, 12, 16, 20, 24. \; l_j = 0.216\,\text{m}, B_j \approx 4.66\,kG$$

$$k_j = -0.1128 \text{ at 2000 A short } 2, 6, 10, 14, 18, 22. \; l_j = 0.246\,\text{m}, \Delta\gamma_t \approx 1.1$$

$$At\ \gamma_t \text{ setting 2 kV, peak current 780 A}, \Delta\gamma_t \approx 0.427, \nu_x \approx 6.7 - 0.01, E_s \approx 4.194 GeV, p \approx 5.02 GeV/C$$

Fixing vertical offset

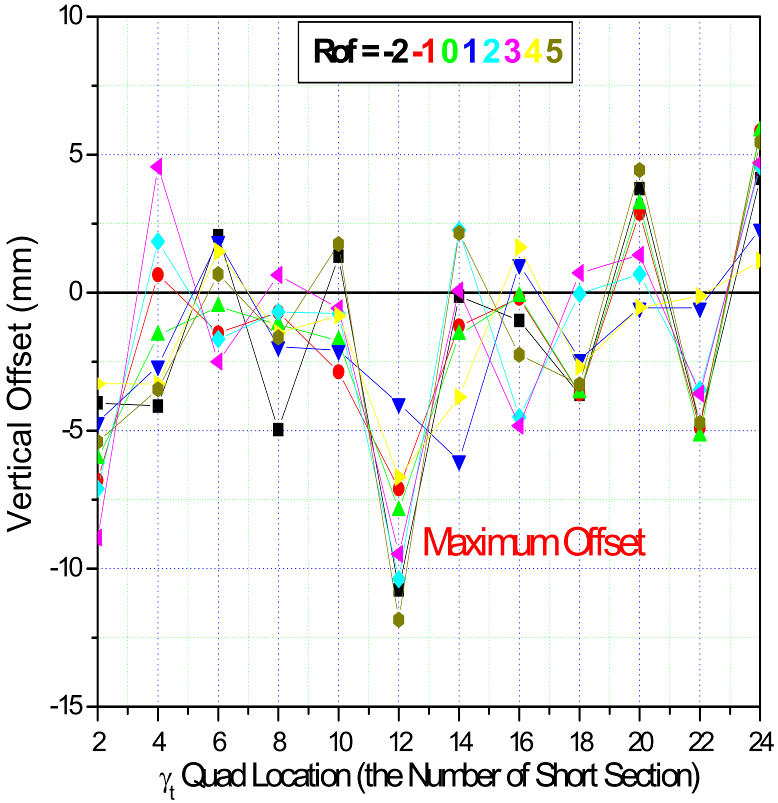


Fig. 1

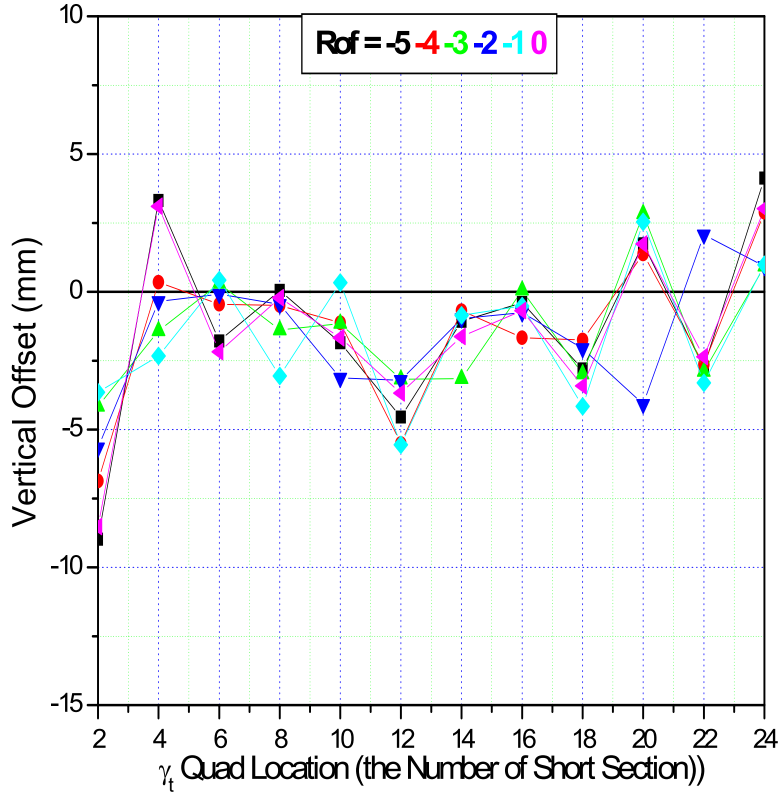


Fig. 2

Based upon the vertical offset measurement in Fig.1, the short 12 γ_t quad was lowered 4 mm. Afterward, the vertical offsets were measured, the results were shown in Fig. 2.

!!!!!!!!!

Additional problem of commissioning γ_t system

- Require the Booster orbit to be centered through all the γ_t quads during the time of pulsing γ_t quads. Once the orbit changes, quad steering will cause problems!

Conclusions

1. The slow acceleration indeed requires less RF accelerating voltages. However, it also slows down the transition crossing rate and makes the beam stay near the transition energy longer, which is likely to make the beam energy loss increase faster with the beam intensity. --We would like to confirm it in the future study by measuring the bunch length near the TC in both 6-GeV and 8-GeV accelerations.
2. Since we had a successful start to fix the quad steering problem, the γ_t system can provide a faster TC.
3. Combining the slow acceleration (gain extra RF power for the high intensity beam) and the γ_t system (make the TC faster), what we might achieve in the future?

More study time!!!

Acknowledge

- Booster Group
- HLRF group
- David Wildman
- Especially thanks Jean Slaughter and Mike Syphers for helping me with the presentation